The problem of Chiral Restoration and Dilepton Production in Heavy Ion Collisions

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In the lecture we review several issues related to recent development in non-perturbative QCD. The "instanton liquid model" reproduces not only the basic vacuum parameters (the condensates) but even hadronic correlators. New information obtained from lattice simulations also confirm it. Meanwhile the model itself was developed into a self-consistent approach, allowing to include 't Hooft interaction to all orders. It was also generalized to non-zero temperatures and high densities. We discuss one issue, displayed by behavior of the pion and rho correlation functions: the former has strong non-perturbative effects at small distances, the latter has none. What happens at $T \sim T_c$ can be answered by dilepton production experiments with heavy ion collisions. The results definitely indicate large changes in spectral density and "melting" of the rho, possibly with reaching chiral restoration.

1   Chiral symmetry and instantons in vacuum/hadronic structure

Let me start the lecture reminding few well-known facts from the textbooks. If quark masses are ignored, the fermion part of the QCD Lagrangian becomes a sum of two independent terms, with left and right-handed quarks. The possibility to rotate those in flavor space *independently* generates *two* additional "chiral" symmetries, $U(1)_A$ and $SU(N_f)$ ones, which have rather different fate.

The $U(1)_A$ one (generated by $exp(i\phi\gamma_5)$ rotation) is explicitly broken by the so called chiral anomaly, and so at quantum level it is simply *not* a symmetry of QCD. The strength of its violation can be seen from a deviation of the pseudoscalar singlet η' mass (959 MeV) from that of a pion/kaon/eta multiplet: note that it is surprisingly large.

The $SU(N_f)$ part of the chiral symmetry is *spontaneously broken*, the QCD vacuum is asymmetric. Its measure is the so called quark condensate $< \bar{q}q >$. By Goldstone theorem, massless modes (rotations to other equivalent vacua) appear, which are pions. General features of their interactions are described by chiral effective Lagrangians.

The main questions we are going to discuss are related to the *underlying dynamics* of these phenomena (and those are rarely discussed in textbooks). However the earliest attempt to explain chiral symmetry breaking was made as

early as 1961 [1]. By analogy to superconductivity, it was shown that sufficiently strong attraction between quark and antiquark in the scalar channel can re-arrange the vacuum, create the quark condensate and a "gap" at the surface of the Dirac sea, the quark effective mass. I would argue below that it is a correct idea, and that understanding of the origin of that attractive interaction and its exact form in QCD was clarified only during the last two decade (see e.g. references in a review [2]).

What was found (first empirically, then from the success of the so called instanton liquid models, then from lattice studies) is that both explicit breaking of U(1) and spontaneous breaking of $SU(N_f)$ $SU(N_f)$ chiral symmetries are driven by instantons.

The first part was easier to understand: as G.t'Hooft have explained in 1976, instantons generate $2*N_f$-fermion effective vertices of particular structure, violating U(1) by flipping quark chiralities. Quantitative part of the U(1) problem was later related to the so called "topological susceptibility" by Witten and Veneziano, and recent lattice studies have left no doubts that those are indeed completely saturated by well-identified instantons.

However spontaneous breaking is not seen at the level of one instanton, one need some knowledge about their ensemble, and particular conditions should be met for it to occur. Otherwise (and this happens at high enough temperature T or large enough number of quark flavors N_f) the chiral symmetry remains unbroken. In 1982 I have fixed the mean density and size of the instantons [10] to be

$$n = n_+ + n_- \approx 1 fm^{-4}; \;\; \rho \approx 1/3 fm \tag{1}$$

It is still rather dilute ensemble because $n\rho^4 \sim 1/81$, but it is dense enough to be in the chirally broke phase!

A decade later lattice configurations were stripped of the "fog" of quantum fluctuations and their classical content was revealed. In Fig.1 from [13] one can see how it works, so that one can see and count instantons. The values given in (1) were basically confirmed.

Instantons do all what the hypothetical NJL interaction was supposed to do. Moreover, they do this job better, because they generate vertices with the particular non-locality: therefore nasty questions related with the non-renormalizable NJL model are naturally resolved, and the NJL cut-off $\Lambda_{NJL} \sim 1 GeV$ (also known as "the chiral scale") was attributed to the instanton sizes. Furthermore, a practical approach was discovered (the "interacting instanton liquid model", or IILM) allowing to include *all* orders in the instanton-induced ('t Hooft) effective interaction.
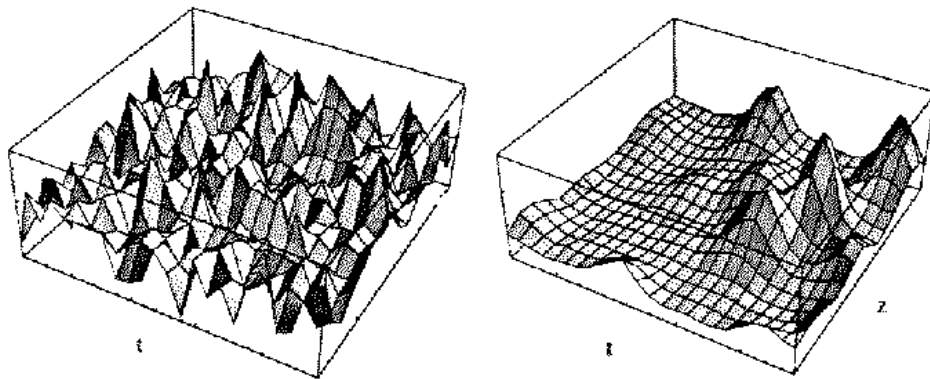
Figure 1: Sample of a gauge configuration before (left) and after (right) cooling.In the latter case instantons are clearly seen. The quantity shown is the action density, and its scale (not shown) is two orders of magnitude larger on the left figure.

But in the last few years it became more and more clear that instantons are responsible for nearly all[a] non-perturbative phenomena associated with light quarks, their propagation in vacuum and bound states. Their masses are mostly the masses of "constituent quarks" we already mentioned, and even their spin-dependent forces seem to be instanton-generated as well[3]. There are direct indications, that not only pions but even the usual mesons like ρ and baryons like nucleon are in a way collective excitations of the chiral condensate.

Finally, to complete the overview of instantons, let me mention that recent progress in supersymmetric gauge theories have indicated some surprising things about them as well. In particular, partial exact solution for $N = 2$ SQCD due to Seiberg and Witten[4]) can be expanded in inverse powers of small parameter Λ/a (where a is the Higgs VEV) at large a, one can see that (apart of a single perturbative one-loop log) all the power terms are $(\Lambda/a)^{4*integer}$, just like multi-instanton contributions should give. The first two orders have been calculated[5] and were found to be exactly right. Although higher orders are not yet done, it is highly possible that that in this theory instantons are the *only* dynamics there is, in the sense that summing the series in their interactions (an analog of the instanton liquid calculation we will discuss below) provides the *exact* result.

The amusing similarity between QCD and (its relative) the N=2 SQCD have been recently demonstrated in [6]. It is related to the issue of already

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[a] With the notorious exception of confinement.

mentioned "chiral scale" 1 GeV. In QCD it is phenomenologically known that this scale is not only the upper bound of effective theory but also the lower bound on parton model description. However, one cannot really see it from the perturbative logs: 1 GeV is several times larger than their natural scale, $\Lambda_{QCD} \sim 200 MeV$. In the N=2 SQCD the answer is known: effective theory at small a (known also as "magnetic" formulation) is separated from perturbative region of large a by a singularity, at which monopoles become massless and also the effective charge blows up. How it happens also follows from Seiberg-Witten solution, see Fig.2. Basically the perturbative log becomes cancelled by instanton effects, long before the charge blows up due to "Landau pole" at $p \sim \Lambda$. It happens "suddenly" because instanton terms have strong dependence on a: therefore perturbative analysis seems good nearly till this point.

For comparison, in QCD we have calculated effective charge with the instanton correction, as defined by Callan-Dashen-Gross expression. All we did was to put into it the present-day knowledge of the instanton density. The resulting curve is astonishingly similar to the one-instanton one in N=2 SQCD. Note, that in this case as well, the "suddenly appearing" instanton effect blows up the charge, making perturbation theory inapplicable, and producing massless pions, the QCD "magnetic" objects. Moreover, it even happens at about the same place! (Which is probably a coincidence.)

The behavior is shown in Fig.2, where we have included both a curve which shows the full coupling (thick solid line), as well as a curve which illustrates only the one-instanton correction (thick dashed one). Because we will want to compare the running of the coupling in different theories, we have plotted $bg^2/8\pi^2$ (b=4 in this case is the one-loop coefficient of the beta function) and measure all quantities in units of Λ, so that the one-loop charge blows out at 1. The meaning of the scale can therefore be determined by what enters in the logarithm.

Recent conjectured correspondence between N=4 SQCD and string theory/SUGRA in 5d anti-de Sitter (AdS_5) space (discussed here in lecture by E.Witten) has also an astonishing instanton connection [7]. In the large N_c limit, and in the weak coupling domain, the results are dominated by specific "multi-instanton molecules" in which all instantons are at the the same point and have the same sizes[b]. This is an example of a (long-predicted) "master field". Any Green function look like propagators going from various space-time points to the point in AdS_5, which happen to be nothing else but the instanton 5 coordinates $d^4zd\rho/\rho^5$. Remarkably, even another 5-d sphere appears, from "di-fermion" condensates, and so the result looks in truly amazing correspondence with the "holographic principle" Witten spoke about.

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[b] They fit there without a problem due to the limit of very large number of colors.
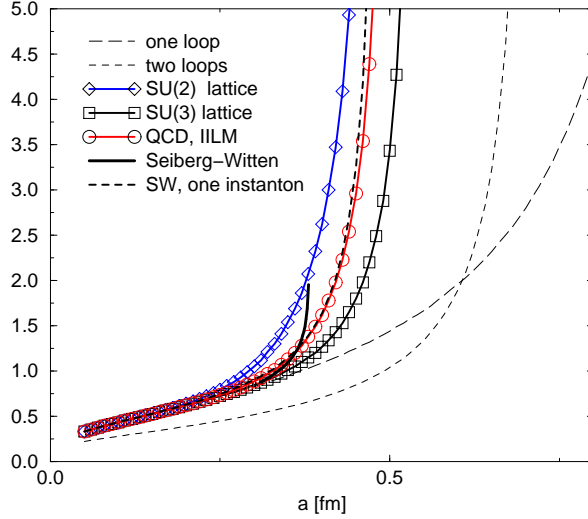
Figure 2: The effective charge $b\,g_{eff}^2(\mu)/8\pi^2$ (b is the coefficient of the one-loop beta function) versus normalization scale μ (in units of its value at which the one-loop charge blows up). The thick solid line correspond to exact solution [4] for the N=2 SYM, the thick dashed line shows the one-instanton correction. Lines with symbols (as indicated on figure) stand for N=0 QCD-like theories, SU(2) and SU(3) pure gauge ones and QCD itself. Thin long-dashed and short-dashed lines are one and two-loop results.

In summary, instantons are responsible for a variety of non-perturbative phenomena, and all of us should study them more.

2   Phenomenology of QCD correlation functions

In this section we go from very exciting recent results advertised above back to simple observations from which the first arguments about a prominent role of instanton-induced effects in QCD were first deduced.

In confining gauge theory like QCD the correlation functions of (gauge invariant) local operators are the best possible tool to bridge the gap between the fundamental fields and physical excitations. The same functions can be calculated at large distances x using the physical states (mesons, baryons, glueballs), and at small x in terms of quarks and gluons. Some of them can be completely deduced from experimental data (see below) and all of them can be obtained from lattice simulations.

Loosely speaking, hadronic correlation functions play the same role for understanding the forces between quarks as the NN scattering phase did in

the case of nuclear forces. In the case of quarks, however, confinement implies that we cannot define scattering amplitudes in the usual way. Instead, one has to focus on the behavior of gauge invariant correlation functions at short and intermediate distance scales. The available theoretical and phenomenological information about these functions was reviewed in[8].

Euclidean point-to-point correlation functions are defined as

$$\Pi_h(x) = \langle 0|j_h(x)j_h(0)|0\rangle, \tag{2}$$

where $j_h(x)$ is a local operator with the quantum numbers of a hadronic state h. Hadronic correlation functions can be written in terms of the spectrum and the coupling constants of the physical excitations with the quantum numbers of the current j_h. This connection is based on the standard dispersion relation

$$\Pi(Q^2) = \frac{1}{\pi} \int ds \, \frac{\text{Im}\Pi(s)}{s + Q^2} + a_0 + a_1 Q^2 + \dots, \tag{3}$$

(where $Q^2 = -q^2$ is the Euclidean momentum transfer and we have indicated possible subtraction constants a_i) and the spectral decomposition ($\rho(s) \equiv \frac{1}{\pi}\text{Im}\Pi(s)$)

$$\rho(s = -q^2) = (2\pi)^3 \sum_n \delta^4(q - q_n)\langle 0|j_h(0)|n\rangle\langle n|j_h^\dagger(0)|0\rangle. \tag{4}$$

A spectral representation of the coordinate space correlation function is obtained by Fourier transforming (3),

$$\Pi(\tau) = \int ds \, \rho(s) D(\sqrt{s}, \tau), \tag{5}$$

where $D(m, \tau) = mK_1(m\tau)/(4\pi^2\tau)$ is the Euclidean propagator of a scalar particle with mass m. Note that for large arguments the correlation function decays exponentially, $\Pi(\tau) \sim \exp(-m\tau)$, where the decay is governed by the lowest pole in the spectral function.

Correlation functions that involve quarks fields only can be expressed in terms of the quark propagator. For an isovector meson current $j_{I=1} = \bar{u}\Gamma d$ (where Γ is only a Dirac matrix), the correlator only has a "one-loop" contribution ($S^{ab}(x, y)$ is the quark propagator)

$$\Pi_{I=1}(x) = \langle\text{Tr}\left[S^{ab}(0, x)\Gamma S^{ba}(x, 0)\Gamma\right]\rangle. \tag{6}$$

The averaging should be performed over all gauge configurations, with proper weight function $\det(i\not{D} + im)\exp(-S)$. Correlators of isosinglet meson currents $j_{I=0} = \frac{1}{\sqrt{2}}(\bar{u}\Gamma u + \bar{d}\Gamma d)$ receive an additional two-loop, or disconnected,

contribution

$$\Pi_{I=0}(\tau) = \langle \mathrm{Tr}\left[S^{ab}(0,x)\Gamma S^{ba}(x,0)\Gamma\right]\rangle - \qquad (7)$$
$$2\langle \mathrm{Tr}\left[S^{aa}(0,0)\Gamma\right]\,\mathrm{Tr}\left[S^{bb}(x,x)\Gamma\right]\rangle.$$

Analogously, baryon correlators can be expressed as vacuum averages of three quark propagators.

In this lectures there is no time to discuss this subject in details (see review [8]), and so we only discuss the amazing difference between the vector (ρ) and the pseudoscalar channels (π, η') observed experimentally. Then we would show how instantons explain this behavior, at least qualitatively. Of course, vector channel is also of special importance because later on we would move to discuss its modifications at high temperatures, as revealed by dilepton production in heavy ion collisions.

In the case of the vector-isovector channel the data from $\sigma(e^+e^- \to (I = 1\ \mathrm{hadrons}))$ and τ-lepton decay[c] .

In Fig.3 and 4 one can see the correlators in π and ρ channels. The functions themselves are strongly falling, and for better understanding it is useful to normalize them to "parton model" (or zeroth-order) perturbative diagrams describing propagation of non-interacting quarks. That is why all figures go to 1 at small x: it is just due to the asymptotic freedom.

There is no place here to describe all the details. Note first how different the phenomenological lines are: in the pion channel there is strong deviation from 1 already at small distances $x \sim 1/3$ fm or so, while in the rho case it is close to 1 up to huge $x \sim 1.4$ fm. Why is that?

Such type of questions were on my mind since the end of 70's, when the appearance of QCD sum rules put those under scrutiny. The rho channels and the like were treated well[9] by including only average fields, the "condensates", but for pseudoscalar and scalar channels this approach has failed completely. It became obvious to me around 1980 that the missing large effect has to be due to instantons.

The qualitative idea is very simple: 't Hooft interaction has quarks of one chirality (say left) and anti-quarks only of the other (right) because this is the only zero modes fermions have in the instanton field. It means large effects in scalar-pseudoscalar channels (as observed) and no effect in vector-axial case. Quark mixing pattern (vectors like ω and ϕ are weakly mixed, while pseudoscalars form combinations known as η, η' which are nearly ideal SU(3)octet and singlet members) supported the same idea. I have calculated

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[c]Those give also the axial-vector a_1 spectral density, from hadronic decays of the τ lepton, $\Gamma(\tau \to \nu_\tau + \mathrm{hadrons})$.
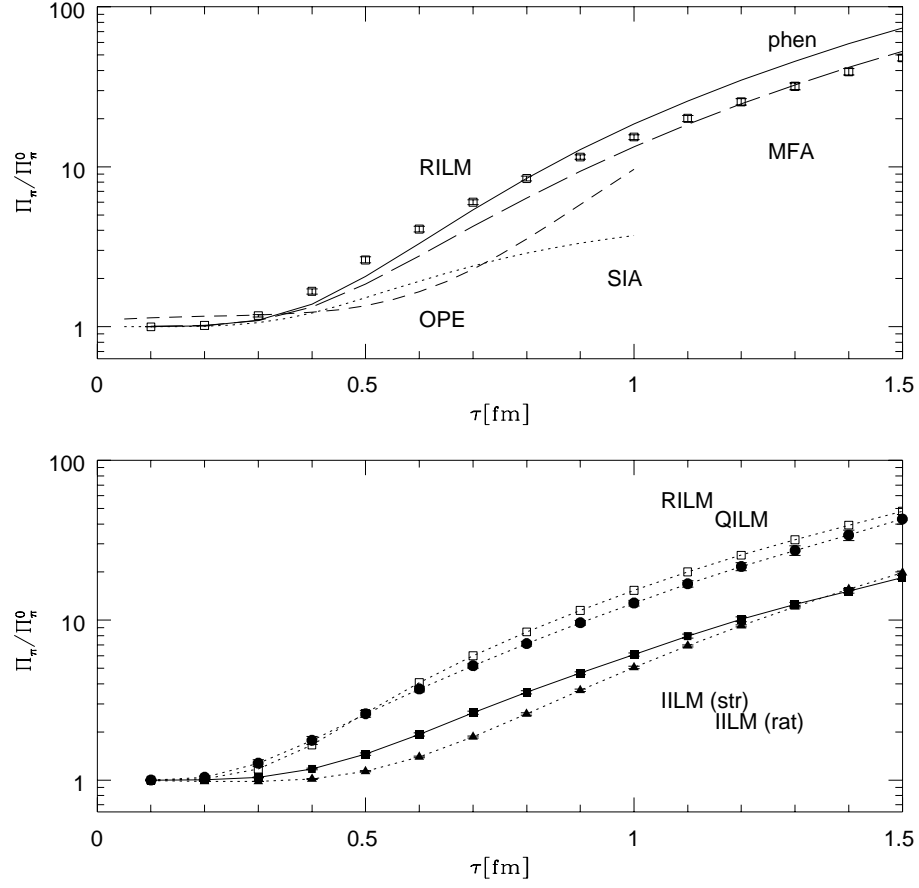
Figure 3: Pion correlation function in various approximations and instanton ensembles. In fig.a) we show the phenomenological expectation (solid), the OPE (dashed), the single instanton (dash-dotted) and mean field approximations (dashed) as well as data in the random instanton ensemble. In fig. b) we compare different instanton ensembles, random (open squares), quenched (circles) and interacting (streamline: solid squares, ratio ansatz solid triangles).
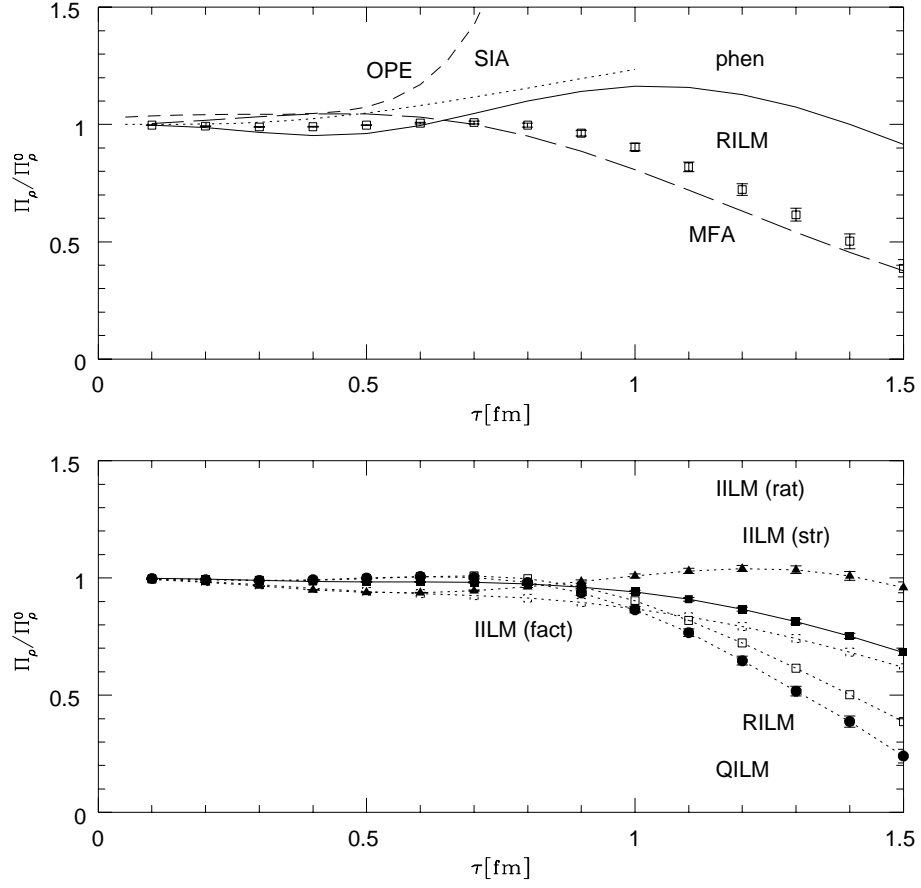
Figure 4: Rho meson correlation functions. The various curves and data sets are labeled as in in Fig.3. The dashed squares show the non-interacting part of the rho meson correlator in the interacting ensemble.

the first-order corrections to the correlators: I got the correct signs for pions (attraction) and the opposite one for η' (repulsion). These correlation function, plus chiral condensates I calculated, has allowed me in 1982[10] to fix (with some confidence) two main parameters of the instanton ensemble (1).

We will return to their discussion below, and now let us conclude with the correlation functions shown in Figs above. The points correspond to our first calculation [11] using randomly placed instantons with such parameters [d]. In spite of admittedly quite primitive approach, the points qualitatively follow these two curves (and many others - see the original paper!) well, reproducing even such details as amazing cancellations of all corrections in the vector channel mentioned above. So, with only 2 numbers (1) and a primitive model, one can calculate the major objects of non-perturbative QCD, the correlation functions, and deriving from them hadronic masses (and much more!) with quite decent accuracy. We have immediately seen that we are on the right track, and further work was not disappointing.

There is no place here to discuss its results in details. Let me only mention that among the ~ 40 correlation functions calculated in the random ensemble, only the η' (and its U(1) partner, the isovector-scalar) were found to behave wrongly: The correlation function decreases very rapidly and becomes negative at $x \sim 0.4$ fm. This behavior is incompatible with a normal spectral representation. The interaction in the random ensemble was too repulsive, and the model "over-explains" the $U(1)_A$ anomaly.

In the meantime we [15] have developed the Interacting Instanton Liquid Model (IILM). Its main element of its partition function is the fermionic determinant done in zero-mode approximation. It means that all orders in 't Hooft interaction. The results obtained in the IILM ensembles do not have this problem. Dynamically it is cased by correlations between instantons and anti-instantons (or the topological charge screening). The single instanton contribution is repulsive, but the contribution from pairs is attractive. Only if correlations among instantons and anti-instantons are sufficiently strong, the correlators are prevented from becoming negative.

Later a very similar situation was found in lattice simulations: the so called "quenched" calculations (fermionic determinant ignored) have produce reasonably-looking results for many channels, but not in the η' one. It was realized once again, that in order to have the QCD vacuum right one really needs to include the effect of dynamical (and rather light) quarks!

Lattice calculations done later has basically confirmed these correlators, especially in baryonic channels. Of course lattice people can actually do much more: to hunt for instantons themselves, calculate their density and sizes, cor-

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[d]This simple model is known as random instanton liquid model, or RILM.

relate them with quark condensate or hadronic propagators, etc. Amazingly, most the quark condensate states (eigenvalues of the Dirac operator with small eigenvalues) were indeed found to be dominated by instantons, see [14].
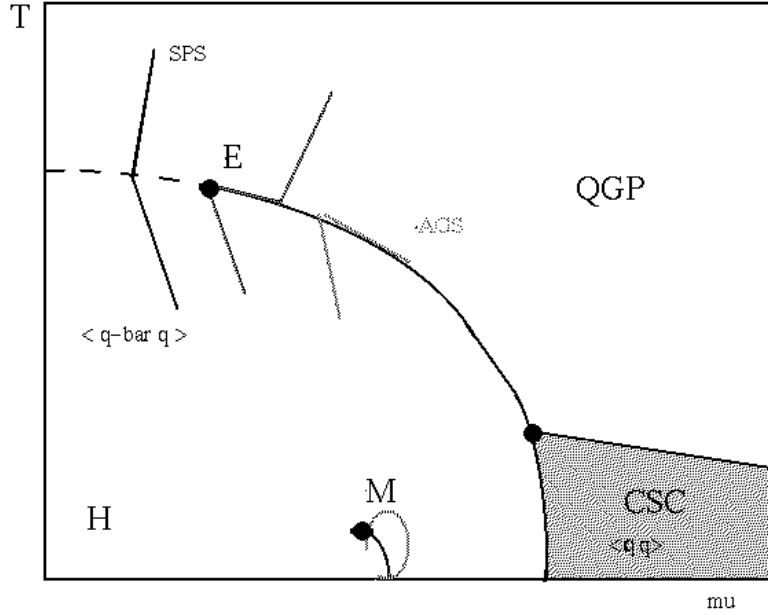

Figure 5: Schematic phase diagram of QCD phases as a function of temperature T and baryonic chemical potential μ, as we understand it today. The phases denoted by H,QGP and CSC are hadronic, quark-gluon plasma and color superconductor, respectively. The dashed line indicate strong cross over, E the endpoint of the 1-st order transition, M is the endpoint of another 1-st order transition, between liquid and gas phases of nuclear matter. Few trajectorries covered in heavy ion experiments are also schematically indicated.

3   The phases of QCD

The QCD under normal conditions is in chirally asymmetric confining phase we are so familiar with: but in the so called extreme conditions it turns to quite different phases. There are at least three different directions in which one expect three different phase transitions. (i) At high temperature $T = T_c \approx 150 MeV$ it undergoes transition to the so called Quark-Gluon Plasma (QGP) phase, in which there are no condensates and color interaction is screened [16] rather than confined. (ii) At high density and low T it is believed to be Color Superconductor (CSC), in which color symmetry is broken by diquark

condensates induced by instantons[17,18]. (iii) At sufficiently large number of flavors $N_f > N_f^c$ it should eventually become chirally symmetric de-confining conformal phase.

The map (for the first two) is shown in Fig.5. We have also shown few schematic trajectories of excited matter, as it expands and cools in heavy ion collisions. One may at least see from those that CSC phase is unfortunately not relevant for them, and so we will discuss mostly the high-T direction in this section. Let me only add few words about the others.

All transitions are believed to be driven by instantons. In particularly, the diquark Cooper pairs are also produced by the same 't Hooft vertex, only Fiertz transformed to diquark channels[e]. The most bound diquark should be the one with spin and isospin zero (ud), and its condensate is the largest, reaching the magnitude of about 100 MeV. Other condensates (e.g. us,ds) are smaller, and there are also smaller $\bar{q}q$ ones, indicated that at small T and high density the chiral symmetry is not restored.

The large N_f direction is less studied. At least one reason for that transition is a tendency of instantons and anti-instantons to be bound by the increasing number of fermion lines connecting them, till finally the "instanton liquid" is gone and only finite pieces with zero topology (or neutral "molecules") are left. Calculations in IILM[15] have found that $N_f^c = 5$.

Now we return to the non-zero T case. Recall that it is incorporated in quantum field theory in a very simple way: the Euclidean time τ is limited by a period $1/T$, the so called Matsubara time. The instanton solution with periodic boundary conditions, called caloron, is well known. Fermionic $anti-$periodic zero mode can also be found.

$$\psi_i^a = \frac{1}{2\sqrt{2}\pi\rho}\sqrt{\Pi(x)}\partial_\mu\left(\frac{\Phi(x)}{\Pi(x)}\right)\left(\frac{1-\gamma_5}{2}\gamma_\mu\right)_{ij}\epsilon_{aj}\,, \tag{8}$$

where $\Phi(x) = (\Pi(x) - 1)\cos(\pi\tau/\beta)/\cosh(\pi r/\beta)$. Note that the zero-mode wave function shows exponential decay $\exp(-\pi rT)$ in the spatial direction, but oscillates in τ. So if instantons are like atoms with the quark zero mode as a wave function, finite T compresses their special extension and enhances the temporal one. (It looks like "pencil-like" atoms in a very strong magnetic field.) That radically change their interactions, which are only strong if instantons are interacting along the time direction. In particular, a pair of such type can be formed, connected to themselves by periodicity.

The main finding in IILM at finite T is that the chiral phase transition is actually driven by a *rearrangement*[19] of the ensemble into a set of instan-

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[e]The perturbative one-gluon exchange also leads to superconductivity, but it is significantly weaker in the transition region and can in first approximation be ignored.

ton anti-instanton "molecules"[f]. Recently the details of this mechanism were significantly clarified, both by numerical simulations[15] and analytic studies[20].

At *sufficiently high* T new non-perturbative saddle point appears, corresponding to a configuration in which the centers are at the same spatial point, but separated by half a Matsubara box in time $\Delta\tau = 1/(2T)$, the most symmetric orientation of the instanton anti-instanton pair on the Matsubara torus. The effect is largest when the molecule exactly fits onto the torus, i.e. $4\rho \simeq 1/T$. Using the standard size $\rho \simeq 0.33$ fm, one gets $T_c \simeq 150$ MeV, the transition temperature found on the lattice.

In a series of IILM numerical simulations[15] it was found that this transition indeed goes as expected, with molecules driving the transition. Furthermore, many thermodynamic parameters, the spectra of the Dirac operator, the evolution of the quark condensate and susceptibilities were calculated[15,20], with results surprisingly consistent with available lattice data. The effect of molecules on the effective interaction between quarks at high temperature can be described by the following effective Lagrangian

$$\mathcal{L}_{\mathrm{mol\,sym}} = G \left\{ \frac{2}{N_c^2} \left[(\bar{\psi}\tau^a\psi)^2 - (\bar{\psi}\tau^a\gamma_5\psi)^2 \right] \right. \tag{9}$$
$$\left. - \frac{1}{2N_c^2} \left[(\bar{\psi}\tau^a\gamma_\mu\psi)^2 + (\bar{\psi}\tau^a\gamma_\mu\gamma_5\psi)^2 \right] + \frac{2}{N_c^2}(\bar{\psi}\gamma_\mu\gamma_5\psi)^2 \right\} + \cdots,$$

with the coupling constant

$$G = \int d\rho_1 d\rho_2 \, \frac{n(\rho_1,\rho_2)}{8T_{\bar{I}I}^2} (2\pi\rho_1)^2 (2\pi\rho_2)^2 \,. \tag{10}$$

Here, $n(\rho_1,\rho_2)$ is the tunneling probability for the $\bar{I}I$ pair and $T_{\bar{I}I}$ is the corresponding overlap matrix element. τ^a is a four-vector with components $(\vec{\tau}, 1)$.

There are qualitative things we would like to point out. First, some spin-zero states (especially pions and its chiral partner sigma) retain significant attraction even above T_c, and are even likely to survive the phase transition as a bound (but not-Goldstone!) state. Second (and maybe relevant for what follows) is that "molecules" generate attractive forces in vector channels as well, which were absent below T_c.

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[f]Note a similarity to the Kosterlitz-Thouless transition in the $O(2)$ spin model in two dimensions: again one has paired topological objects, vortices in one phase and random liquid in another. The high and low-temperature phase change places, though.

4 The "Little Bang" versus the Big Bang

In general, the field of high energy heavy ion collisions is now among the most rapidly developing fields of physics. It is fun to notice its parallels to cosmology, which goes beyond methodic similarities to amusing parallels in timing of some recent achievements.

Appearing at the intersection of high energy and nuclear physics, these studies are now mostly carried out at CERN SPS (E=200 GeV*A) and Brookhaven AGS (E=2-11 GeV*A). Their main goal is production of hot/dense hadronic matter with the energy density of the order of few GeV/fm^3 and study of its properties. Especially interesting are *early* stages of the collisions, in which theory predict existence of the QCD phase transition into a new phase, called the Quark-Gluon Plasma (QGP)[16]. The Big Bang of course proceed via T axis in Fig.5 since the baryonic density is tiny. For comparison we have indicated schematic location and shape of some paths corresponding to current heavy ion experiments.

The first obvious connection between the "Little Bangs" created in these collisions and cosmological "Big Bang" is that both are violent explosions. Expansion of the created hadronic fireball approximately follow the Hubble law, although anisotropic ones. The *final* velocities of collective motion in both cases have been a matter of debates 3-4 years ago, but now are believed to be reasonably well known. (The main problem here is of course the reliable separation between directed collective motion and chaotic thermal one.) For central heaviest ions the mean transverse velocity reaches about 1/2 c, and so not only longitudinal but also transverse explosion is relativistic.

The second important point is that (also in both cases) the underlying history of matter acceleration, which led to this final velocity, remains subject to theoretical speculations. In ion collisions this was determined by the Equation of State (EoS), which is believed to be very soft near the QCD transition, and to find this fact would be very important[g]. Experimentally the problem is related with the fact that observed hadrons (like microwave cosmic photons) are seen at their *freeze-out stage*, the moment of last interaction. In order to look deeper, one uses rare particles with smaller cross sections, such as Ω^- hyperons, which decouple earlier. Indeed, those show much smaller flow. (Cosmologists solve the problem by looking at very distant Galaxies, which also tell you about a velocity at earlier times.)

The third type of comparison I would like to make here deals with the issue of fluctuations. Very accurate and difficult measurements of the microwave

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[g]One way to do it, is to measure accurately the energy/centrality dependence of the collective flow.

background anisotropy were made, and have found (apart of trivial dipole component) a trace ($\sim 10^{-5}$) of it originated from plasma oscillations at photon freeze-out time. It is seen as some structure with angular momentum $l \sim 100$. In heavy ion collisions a similar work is in progress. The dipole and quadrupole components in azimuthal angle are measured and are being analyzed: those come from asymuthal asymmetry of initial conditions, for non-central collisions. We do not yet see reliable signals of higher harmonics, but I think there is a chance to see eventually " frozen plasma oscillations" in this case as well. After all, we have millions of events, while The Big Bang people are restricted to only one!

There is no place here to describe heavy ion physics in any details. Let me just indicated where we stand now. In some respects the heavy ion program was very successful. Let me mention one major issue, which I think by now is pretty much resolved. It is the question (asked by numerous sceptic s over the years) whether the system produced in heavy ion collisions is or is not large enough to be treated as a macroscopic one. The question has been answered positively, as evidences for "flowing" locally equilibrated hadronic matter became more and more convincing. Recent data on event-per-event fluctuations from CERN NA49 [21] have also demonstrated, that in all quantities measured so far the event-by-event distributions show narrow Gaussian-type histograms, valid for few orders of magnitude without any visible "tails". It is very different from how pp data look like, or from a superposition of NN collisions. It shows that we are in fact studying here an excited hadronic system which is very different from that produced in pp collisions, and in fact a much simpler one[h] to describe.

On the other hand, its main goal – demonstration of the QCD phase transition line or presence of QGP – is not yet reached. From many observables we see that we definitely are at the conditions which are the edge or even beyond the transition. The strong interaction in the system, as it expands and cools, erases most of the traces of the dense stage.

5   Dilepton production in heavy ion collisions: theoretical considerations

One possible way to study the earlier stages is to look for "penetrating probes", production of *dileptons* and *photons*. (Another possibility is to look for signals which are *accumulated* during the evolution: the well known examples include

[h]I of course mention it in order to tease high energy physicists, who are proud of studying simple fundamental topics only, blaming nuclear physicist of usually dealing with a complicated mess. In this case it is the other way around, due to significant simplifications arising in the macroscopic limit.

excessive production of strangeness or charmonium suppression,see lecture by D.Kharzeev). Dileptons, unlike secondary hadrons, are produced at relatively early stages of the collisions. Therefore we expect to see that hadronic properties are *modified* in hot/high density hadronic matter, and at high enough collision energy we expect to observe the radiation from QGP.

Theoretical calculation of dilepton production is usually made in two steps: the first is the determination of the *production rate* in equilibrium matter, the second (to which I would not go at all) is the space-time integration over expansion of the matter during heavy ion collisions.

The simplest (I would call them 0-th approximation) models for dilepton production rate are based on well-tested processes: (i) the usual $\pi\pi$ annihilation in hadronic phase at small T , and (ii) it is $\bar{q}q$ annihilation in QGP for large T. (The second process is similar to familiar Drell-Yan process, only in thermal ensemble.) those two basic processes can be included in the "standard rate" formula:

$$\frac{dR}{d^4q} = \frac{\alpha^2}{48\pi^4} F exp-(\frac{q_0}{T}) \tag{11}$$

where the rate R is counted per volume per time, q is 4-momentum of the virtual photon ($q^2 = M_{e+e-} = M^2$), F is the usual pion form-factor in the pion gas, which can be written in standard vector-dominance form. In QGP F is a constant, up to small corrections, and we will use this "partonic" rate below as our "standard canle", the comparison benchmark.

$$F = \begin{cases} F_H \stackrel{\text{def}}{=} \frac{m_\rho^4}{[(m_\rho^2-M^2)^2+m_\rho^2\Gamma_\rho^2]}, & \text{(Hadronic)} \\ F_Q \stackrel{\text{def}}{=} 12\sum_q e_q^2 \left(1+\frac{2m_q^2}{M^2}\right)\left(1-\frac{4m_q^2}{M^2}\right)^{\frac{1}{2}}, & \text{(QGP)} \end{cases} \tag{12}$$

is a constant in QGP

The "1-st approximation" models try to describe what happens in between these two limits, especially in hadronic matter below but close to the transition. It is based on the notion of "meson modification" in matter. We know from standard nuclear physics that the *nucleon* properties such as effective mass are modified in nuclear matter. There are of course many other examples in condense matter physics, in which the atomic states are shifted/broadened by the medium. So the modification of vector $in-matter$ spectral density was usually discussed in terms of shifts of the *vector meson masses*. At low density one can relate modification of mesons (e.g. of ρ) to the $\pi\rho$ and $N\rho$ forward scattering amplitudes, or momentum-dependent optical "potentials", which

predict relatively modest shift of m_ρ downward and some broadening. When matter is no longer dilute and modifications are no longer small, one should do some re-summations. As good example of such kind or work let me mention Wambach-Chanfray-Rapp approach [27], in which very strong broadening of ρ meson was predicted, based on properties of $\rho - N$ interaction/resonances. One can also understand this broadening as due to mixing between ρ with excitations of the lowest baryon resonances, such as $N^*(1520)N^{-1}$ (resonance plus a nucleon hole).

Connecting hadronic masses to chiral breaking and in particular to $< \bar{q}q >$ has lead to the idea that *all* hadronic masses were predicted to vanish at $T \to T_c$. This reasoning has culminated in the so called *Brown-Rho scaling* [23], according to which all hadronic dimensional quantities get their scale from $< \bar{q}q >$ and therefore

$$\frac{m(T)}{m(0)} = (\frac{< \bar{q}q(T) >}{< \bar{q}q >})^p \tag{13}$$

where p is some power (e.g. dimensional 1/3). Finite T/density QCD sum rules (see e.g.[24] and references therein) also relate hadronic properties to the quark condensate $< \bar{q}q >$, and therefore they predict the power p=1.

One can also find explicit analytic example of similar behaviour near the phase boundary between chirally asymmetric and comformal phases of QCD: in this case hadronic scale driven by $< \bar{q}q(T) >$ can be many orders of magnitude smaller than the basic "partonic" scale of the theory Λ. On the other hand, at the finite T phase transition the "instanton molecules" mentioned above may be important reason for the deviation from such scaling, because they generate new interaction in the vector channel, unrelated to $< \bar{q}q >$.

Further development along such lines lead to what I would call the 2-nd approximation models such as Li-Ko-Brown model[28] in which all vector meson masses are shifted proportional to mesonic density with Walecka-type mean field. Those models were implemented as codes, self-consistently describing the evolution of matter and the mean field.

Let us see how these models compare. In Fig.6(a) one can see the rates. The pion annihilation curve show the standard ρ peak, while for example the "realistic" curve including in-matter effects according to Rapp et al[i]. The widening of ρ plus Boltzmann factor which emphasizes small masses have changed this curve significantly. Note also one striking fact: for the most

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[i]The corresponding theory is subject to many tests and incorporate a lot of knowledge about cross sections and $\rho - N$ resonances, and its details keep changing. I am greatful to Ralf Rapp who provided this updated figures prior to publication.

important masses $M = .3 - .6 GeV$ the "realistic" curve obtained in a complicated calculation is not so far from the "partonic" one, which would correspond to just ideal gas of quarks and anti-quarks.

Another way to demonstrate to the students here that the matter is by no means settled, even qualitatively, is to mention quite opposite suggestions about hadronic properties close to (or even above) T_c which can be found in literature. For example, effective Lagrangians lead to a prediction of *rising* $m_\rho(T)$ [25], moving by T_c about half way toward the mass of its chiral partner a_1. Do we have any firm theoretical benchmark here?

One definite thing is that chiral restoration demands that vector spectral density should become identical to that of the *axial* current. Indeed, the only difference between them is related with chirality-flipping terms. More specific form of this statement can be written as a set of Weinberg-type sum rules [26], related the certain moments of the difference with a particular chirally-odd quantities like $< \bar{q}q >, f_\pi$.

However, actually we expect more from chiral restoration than just shifting ρ and a_1 to the same point, and thus eliminating the difference. The high-T phase is expected to be the QGP, with only perturbatively interacting quarks and gluons. If so, one may expect that delta-functions (resonances) would be effectively gone, and the threshold energy E_0 move down, somewhere to twice perturbative quark mass in QGP. This is basically what CERN dilepton experiments such as CERES have indeed indicated (And that is why I have found this subject to be worth presented at this prestigious school!) Very roughly speaking, the data are consistent with nearly "partonic" production rate, and not only at very high density/temperatures in QGP, but already in hadronic phase close to T_c.

What is still missing in theory, in my opinion (the "3-ed generation models") is models based on more fundamental level, capable of explanation of the modified basic interactions between quarks. Those should be able not only predict changes of masses, but also of condensate themselves and other parameters of the spectral density. I think the most important issue is actually the modification of the "duality scale", the threshold" E_0, above which parton results are dual to hadronic calculations. In vacuum this parameter is around the mass of the second resonance, $E_0 = 1.4 - 1.6$ GeV, related to "gluon condensate" by the QCD sum rules. What is puzzling here, is that at $T \approx T_c$ we have in these collisions this parameter E_0 seem to become very small, not larger than about .3 GeV or so, while the gluon condensate cannot dramatically change from T=0.

6 Dilepton production in heavy ion collisions: experiments

There are three dilepton experiments at CERN SPS: (i) CERES (NA45), which study the low mass (M=0-1. GeV) e^+e^- pairs, (ii) HELIOS-3, which study medium mass $\mu^+\mu^-$" M=1-2 GeV, and (iii) NA38/50 concentrated on high mass $\mu^+\mu^-$. All three see quite significant enhancement over "standard sources", ranging from factor 5 at CERES (in some kinematic region) to about 3 at NA38/50[j] at M=2-3 GeV. These numbers are maximal, corresponding to the most central heavy ion collisions, like Pb Au. Let me also mention that old Bevalac dilepton energy experiment, at E$\sim$ 1 Gev*A also found strong enhancement: these results would be soon tested at SIS in Darmstadt.

I have no place to explain that experimentalists have done their homework, they have measured the dilepton production in pp (or p-Be) and found the results completely consistent with a "cocktail" of known effect, such as π, η and resonance decays. CERES data for heavy (PbAu) ion collisions are shown in Fig.6(b): one can clearly see that relative to free pion gas annihilation (the no-in-matter-modification curve) there is a low-mass *enhacement*, combined with the *deficite* in ρ, ω mass region. The curves related with "shifted" ρ mass a la Brown-Rho or "realistic" widened ρ are consistent with the data. More detailed data (not shown) indicate that these effects exist only for low p_t dileptons, indicated that it is indeed an in-matter effect. It excludes some models (like that based on P-wave $\rho - N$ resonances. CERES has been upgraded and the 98 run should provide much better resolution and signal/background ratio, although comparable statistics. Helios-3 data (not shown) are also provide evidences for in-matter production, which is consistent with these two theories, or our benchmark, the "partonic" rate.

At the present level of accuracy, it is only possible to conclude that the spectral density of in-matter excitations is indeed qualitatively different from in-vacuum one. The ρ peak seem to be gone, and the spectral density looks close to "partonic" quark continuum we expect to see in QGP. It is actually quite puzzling fact, since only small fraction of the space-time volume contributing to dilepton production is expected to be QGP above the transition, while most of it should still be in hadronic phase.

Let me at the end mention few unresolved issues. One is what happens with ω peak: it will be answered by CERES soon. The other is whether in-matter modification is the mesonic or baryonic effect. It could be tested by going to RHIC (very small baryon/meson ratio) and SIS (large baryon/meson ratio). Finally, the NA38/50 enhancement is not yet analyzed: it may be due

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[j]In the "very high" mass region, M¿3 GeV, dilepton production is well described by simple partonic Drell-Yan process.

either to true QGP dileptons or the enhanced charm production. Both are very exciting possibilities, maybe a decisive clue to the QGP.

At the end of this section, let me make some remark about status/history of the dilepton experiments in general. These kind of experiments are generally much more difficult compared to measurements of hadronic observables. In addition to large background which need to be rejected, they are related with smaller cross sections and are significantly limited by its statstics/number of runs. Historically dilepton experiments have a tendency to came too late. At Berkeley BEVALAC the DLS spectrometer had so limited number of runs that its results will probably be never understood. The Brookhaven AGS program had no dilepton experiments at all. The CERN SPS program has 3 experiments mentioned above, and those have produce exciting data. However, they all have one run a year, for few weeks. The data are still statistics limited and had so few runs that one cannot trace dependence on even such major parameters as collision energy or atomic number. And the end of SPS heavy ion program may be already at sight.

Next year a dedicated relativistic heavy ion collider (RHIC) would start its operation at Brookhaven. It would collide 100 GeV per nucleon beams of Au nuclei with each other, and among its detectors one (PHENIX) is mostly devoted to electron, muon and photon physics. Heavy ion program is also a part of LHC project, with one common European heavy-ion-oriented detector ALICE. With those facilities, we should be able to penetrate deeply into domain of the QGP phase.

7   Conclusions and discussion

I have argued that *instantons* dominate nearly all aspects of light quark physics in QCD. The instanton ensemble is dense enough to be in a disordered phase, so that their zero modes are collectivized into a "zero mode zone" with small Dirac eigenvalues. These states form the non-zero quark condensate. As shown both on the lattice and in the instanton models, these states dominate also light quark propagators and hadronic correlation functions at large distances.

At temperature $T > T_c \sim 160 MeV$ the chiral symmetry gets restored because random instanton ensemble breaks into finite clusters. The instanton simulations show that these clusters are particularly structured instanton-anti-instanton pairs or "molecules". Lattice simulations had only partially supported this scenario: larger-volume and smaller-mass simulations are needed to clarify this issue.

At low T and high density there is another QCD phase, known as color superconductor. In many respects it is closer to electroweak theory, because

the colored diquarks condense and break color symmetry, like Higgs particles. It is interesting, that with the inclusion of strange quarks one finds a very particular hierarchy of the condensates, including chirally asymmetric $< \bar{q}q >$.

In our discussion of the QCD vacuum/hadronic structure we have pointed out a striking difference between the spin zero channels (such as π, σ, η') and vector $(\rho, \omega, \phi, a1)$ ones. The former show strong deviations from parton behavior at small distances, the latter do not. Now one can ask what happens with inter-quark interaction as T is approaching T_c from below. Theoretically one finds significant changes in masses of all scalars, but those is difficult to observe. However vector spectral density is directly measurable in dilepton experiments.

All three dilepton experiments at CERN: CERES, HELIOS-3 and NA38/50 see strong enhancements relative to "trivial sources", especially at small p_t. It is clear from the data that in-matter production of dileptons is significant. Furthermore, a modification (or maybe even complete melting) of ρ resonance seem to take place. Some success in phenomenological treatment with shifted masses and modified widths was achieved at hadronic level. However at more fundamental quark level we still do not quite understand what is the effective interaction between quarks in the vector channel at $T \approx T_c$. It looks like "partonic" rate approximately describes the production at $T \approx T_c$ in the whole of domain of hot/dense matter created at SPS, up to very small masses of the order of .3 GeV. This is rather surprising. If so, it which would imply that we see some "premature" chiral symmetry restoration, even before the QGP phase has really become dominant. Much more work, both experimental and theoretical, is needed to clarify this outstanding claim.

8   Acknowledgments

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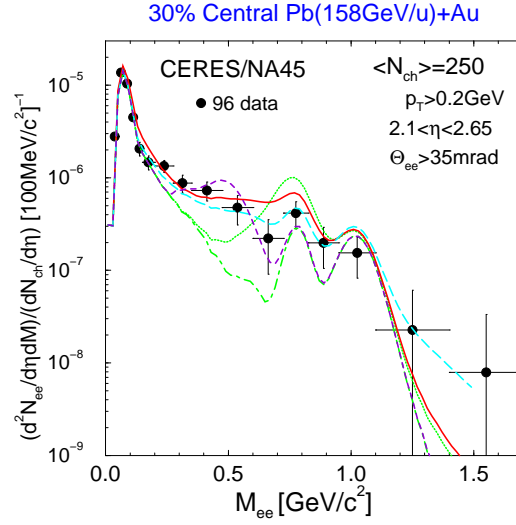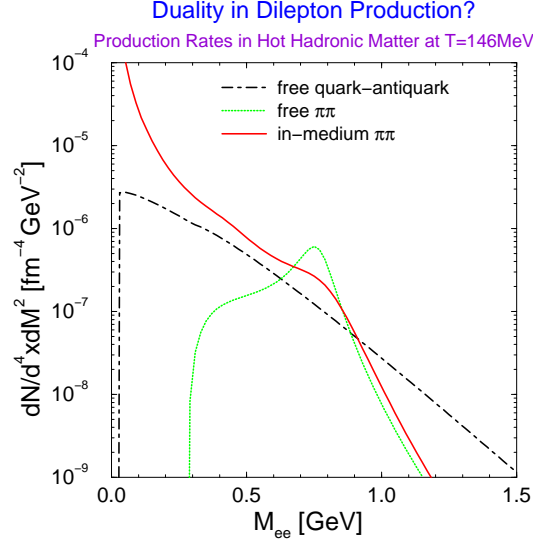Figure 6: (a) Comparison of dilepton production rates: thermal pion gas, "partonic" (dash-dotted) "realistic" one (from Rapp et al). (b) Comparison of CERES 96 data for mass spectrum of the observed dileptons with several theoretical calculations: no in-matter production (dash-dotted), no in-matter modification (solid with ρ/ω peak), the Brown-Rho scaling (dashed with a peak at M≈.5 GeV), hadronic rho widening (solid) and pure "partonic" rate (dashed).